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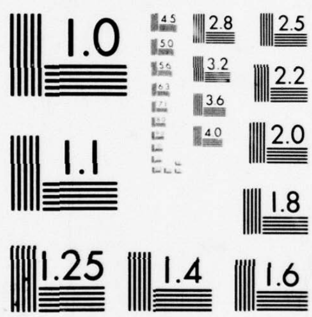

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Project Report

ETS-30

The Current State of GEODSS Astrometry

L. G. Taff
J. M. Poirier

27 January 1978

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THE CURRENT STATE OF GEODSS ASTROMETRY

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PROJECT REPORT ETS-30

27 JANUARY 1978

LEXINGTON MASSACHUSETTS

ABSTRACT

This report summarizes the present status of the implementation of real time positional data reduction at the GEODSS Experimental Test Site. The report embraces definitions of the various procedures which have been explored, their respective futures, their accuracies and precisions, their source files, and how the operator interacts with these procedures in a computer controlled electro-optical artificial satellite observatory. The Introduction contains references to the documents that describe the underlying philosophy, theoretical and practical foundations, and computational details.

CONTENTS

I. INTRODUCTION

This report discusses the current state of the real time implementation of astrometric reduction procedures at the Experimental Test Site (ETS) of the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system. The interaction with the telescope's operator, the future of the sundry means of performing the necessary data reduction, a brief discussion of accuracy and precision, and the realization of a combined astrometric-photometric calibration are also presented. The fine points of the rationale behind the various alternatives, their theoretical development, and the mathematics of their execution have already been dealt with, at length, in other documents (1-11).

Specifically short discussions of the rationale upon which the techniques rely, the nature of the results to be obtained, the necessity of external checks and balances, the tradeoff analysis involved in choosing one technique instead of another, the desirability of operator aids in the form of graphical displays, the nature of the operator/computer interface, and the future of each technique are presented. Detailed documentation of the software will appear later. Moreover, since this report is not self-contained, a deeper understanding can only be acquired by becoming intimately familiar with the above quoted references. Our purpose here is to be informative and to assist as wide an audience as possible in becoming knowledgeable about GEODSS astrometry.

We begin first by describing the techniques for positional data reduction that have been considered, in depth, during the past two years.

Next, a very short reminder of the complexity of the reference star reductions is given. This section also mentions the corrections that must be applied to the raw observational data. Following this are descriptions of the two procedures completed at this time.

II. DEFINITIONS

A. GLOBAL CALIBRATION

This phrase has evolved to mean the construction of a mathematical model (continuous or discrete) which, in the space accessible to the telescope, accounts for tube flexure, droop, optical axis misalignment, bending, clock error, index error, collimation error, polar axle misalignment, drive instabilities, etc., that occur in the mount, telescope itself, electro-optical camera, and their various couplings. It is known that for certain configurations the synthesis of such a model is both possible and profitable. Indeed, this was the first technique to be explored in a complete theoretical and experimental manner. It is necessary that the results be stable over long periods of time (e.g., seasonally at least) for this technique to be beneficial. While stability existed in the functional form of the error analysis, there was little, on time scales as short as 20^m, in the parameters of the model. Hence, this was abandoned as a practical alternative. The possibility of its resurrection in a different coordinate system is undergoing investigation by John Sorvari.

Once set up, this procedure has the advantages of being both hidden from the operator, of not requiring his implicit or explicit cooperation, and of using the absolute minimum amount of future telescope time. It would not provide external error estimates, it would be susceptible to non-reproducible temporary hardware failures, it is conceptually the simplest to envision and implement, and would require minimum maintenance. Operator aids would be superfluous and accuracy would be limited by the inherent instrumental random errors.

B. SINGLE STAR CALIBRATION

SSC now refers to a specific procedure currently being fully integrated into the real time system as an operational tool. It is the first step in performing a real time local reduction of the position of the object of interest. The assumptions and presumptions made may be summarized in the form that whatever causes the mount/telescope/electro-optical camera combination to deviate from perfection is local in both direction and time. Hence, a differential correction will suffice. The final datum consists of the topocentric position of the artificial satellite. No external or internal statement regarding precision is possible. It is also susceptible to non-reproducible temporary hardware failures and it will not work at small ($\simeq$ 10-15^{o}) polar distances. Clearly it could be extended to include 2,3,... reference stars and still retain its essential character (i.e., its intrinsically local nature). In our opinion this is not warranted when the increased precision is weighed against the increased costs; this is especially true in view of the existence of PLC (cf. §II C below).

SSC requires the operator's explicit intervention in bringing a pre-selected reference star to the optical axis of the telescope/electro-optical camera combination. Hidden from the operator is the logic which chose this particular star (essentially the closest one in the source catalogue used for this purpose), the complete second-order reduction from mean place to topocentric place, and the differential application of the corrections. An experienced operator can perform the entire procedure in less than 10^{s}.

C. PRECISION LOCAL CALIBRATION

PLC too refers to a specific procedure currently completing its integration into the real time system of the ETS as an operational tool. We view it as the ultimate in performing a real time local reduction of the position of any celestial body. Here the assumptions and presumptions that have been made are minimal. The final data consists of the topocentric position of the object of interest and unbiased, external, total values for the errors in each coordinate. The philosophical basis for PLC is derived directly from the plate reduction techniques of classical photographic astrometry. Although it will work poorly at small polar distances, the extension to the poles, should it prove necessary, has already been developed.

PLC requires even more operator cooperation than does SSC. This is because several stars must be brought to the fiducial mark instead of one (5 at present). Beyond the operators' ken is the logic behind the reference star selection, a complete, simultaneous, second-order reduction from mean to topocentric place for these stars (which is performed differentially), and the nature and complexity of the data reduction. An experienced operator can perform the entire procedure in less than 1^m.

D. JOINT ASTROMETRIC - PHOTOMETRIC CALIBRATION

Conceived of initially as the ultimate time-saver, this technique refers to the simultaneous use of the same reference stars to reduce both optical and positional data. The data base for performing this has recently been completed, but its culmination has been delayed by the separate development of SSC and the practical realization of photometric observing and reduction techniques of the appropriate precision. With the experience gained so far, we see no problems in completing its implementation.

III. ASTROMETRY

The combination of using a non-inertial coordinate system, of being forced to use an observing platform which itself is undergoing complicated motions, of the inherent motions of celestial bodies, of the effects on the propogation of light by the earth's atmosphere, and the necessity of overcoming all of these complications in a slide-rule only age has resulted in a cumbersome computational edifice. In particular, the effects of lunisolar precession, planetary precession, nutation, polar wandering, annual aberration, annual parallax, diurnal aberration, diurnal parallax, stellar aberration, proper motion, foreshortening acceleration, planetary aberration, astronomical refraction, and parallactic refraction need to be allowed for when reducing a celestial object's mean place to true place to apparent place to (finally) topocentric place. Similarly, as the ultimate use to which the data is to be put dictates, the effects of these must be undone. Fortunately, the theoretical and computational developments for each of these terms was completed some time ago (by others).

Our treatment of these entanglements is rarely rigorous. Nonetheless, the demonstrated (accidental) accuracy is $0\overset{''}{.}01$ (5 parts in 10^{-8}). The large, complex, software that executes these corrections has been exhaustively reproduced by hand. Whenever possible, competing (and completely independent) computational methods were employed. Further elucidation may be found in references.

IV. SINGLE STAR CALIBRATION

The source catalogues for the reference stars to be used in the SSC procedure are the FK4 (12) and its Supplement (13). A selection based on apparent magnitude [$V \leq 6^{m}.25$ or if B-V was known $m_{20} \leq 6^{m}.50$ (cf. 11)] was then effected. The final SSC reference catalogue consists of 2859 stars (out of a possible 3522) all on (or defining) the FK4 reference system. Our current information regarding the FK5 leads us to believe that when it appears (mid 1980's) it can supplant the current SSC catalogue. These stars are bright and uniformly distributed over the celestial sphere. Hence, an operator display (in the form of finding chart) was judged to be superflous.

The real time reduction to topocentric place is governed by a program called REDUCE. It uses other programs called SITCOR (site coordinates), YRCON (constants that vary only on a time scale of one year), GETCON (which accesses the Besselian Day Number protected disc partition), DAYNUM, and REFRAC (which handles astronomical refraction). Non-real time long term reference star reductions are handled by two other programs (UPDATE and TOYR). Ephemeris time is extrapolated from Coordinated Universal Time (UTC) and used to compute instantaneous values of the Besselian Day Numbers.

The choice of the reference star to be used is vested in OPTDIS (optimum distance). This program efficiently searches an especially constructed version of the SSC catalogue which permanently resides on another protected disc partition. The application of the differential corrections to the direction of the object of interest is handled by ONESTAR.

Communication between the SSC overlay and its associated task and the telescope operator occurs through a CRT display device and three buttons on the operating console. An example of the dialogue is given in Fig. 1. One button serves to initialize the entire process, one serves to signal the successful completion of the operator's contribution in bringing the reference star to the fiducial mark on his video monitor (SSC itself automatically handles the gross movement of the telescope), and the third allows for changing one's mind or being unsuccessful in the alignment process (for any reason whatsoever). In addition to the visual display of the results, it is also recorded onto magnetic tape and in hard copy form (via a line printer). If the observed object was an artificial satellite, its identification number is also recorded. Naturally, the time and other pertinent information is recorded too.

Preliminary experimental results imply that this technique is solely limited by inherent instrumental errors. The principal contributors to this are the reading of the full resolution of the telescope's shift recorders, the discrete nature of the ultimate collimation, and the size of the resolution element in the electro-optical camera. No single star procedure can overcome these. However, a multiple star version with the same philosophy would be expected to defeat this limit. In our opinion, the development of such a procedure is unwarranted. This is based on our analysis of the expected accuracy, the lack of an external (or internal) error estimate, the computation involved in selecting the optimum geometrical

configuration of the reference stars, and the required expenditure of the telescope time. Instead, we developed the Precision Local Calibration Technique.

ETS-30 (1)

```
ONESTAR CALIBRATION ON ZET PER S-20 MAG = 2.9
LOCATION:  POS ANG(DEG) = 42.2 DISTANCE(DEG) = 2.47
IF POSSIBLE BORESIGHT THE STAR AND PRESS DATA BUTTON
IF NOT PRESS NO DATA.
TOPO POSITION OF UNKNOWN IS RA(H,M,S) =  3 46 38.6  DEC(D,M,S) =  30 8 5
TELE ERRORS ARE (ARC SEC) RA*COS(DEC) =   9.1 DEC = -27.0 POS = 28.5
```

(Message if unable to boresight star)

PROGRAM WILL ABORT

(Message if unable to activate associated task)

ACTIVATION ERROR 1

Fig. 1. Interactive dialogue for SSC. Operator responses are in lower case letters.

V. PRECISION LOCAL CALIBRATION

The source catalogue for the reference stars to be used in the PLC procedure is the Smithsonian Astrophysical Observatory Catalogue (14). No arbitrary selection has been induced. The stars in this catalogue are uniformly distributed on the celestial sphere with a guaranteed minimal density of four stars per square degree. The mean density is 6.3 stars/square degree. The stars may be as faint as $m_{pg}=12\overset{m}{.}0$. Furthermore, because selection effects other than magnitude completeness dominated the decisions on which stars to include, at $m_{pg}=9\overset{m}{.}0$ one-half of the stars visible to the operator are not included in the SAOC. This situation worsens exponentially with increasing m_{pg}. For this reason, a graphical display (in the form of a finding chart) was constructed as an operator aid. To minimize confusion, all non-stellar extra-solar system celestial objects with $m_{pg} \leq 12\overset{m}{.}5$ are also displayed. The inclusion of asteroids awaits a sufficiently precise and quick ephemeris generator for them.

The display is controlled by table-lookup routines (FETCHS for the stars, FETCHG for the non-stellar extra-solar system objects, and FETCHA for the minor planets; FETCHS and FETCHG are modifications of software originally developed by V. Stacey), a coordinate transformation routine to correctly orient the display named PREPVG (prepare the Vector General; Vector General is the trade name of our principal graphics display monitor), the DISPLAY software which, in combination with an external plotting package, actually generates the display, and several smaller software packages which are peculiar to the rationale of the PLC concept.

The real time reduction of the chosen reference stars is governed by a program which differentially performs the function of REDUCE (SREDUCE). The choice of the reference stars ultimately used, from among the stars in the immediate vicinity, is governed by GEOM (as it is the geometrical configuration of the reference stars about the celestial object of interest which predetermines the final accuracy). The area covered by the display is ordained by the field of view of the telescope on the one hand and the density of the SAOC on the other hand. Currently the minimum number of stars (5) is implemented. The operator does not control this. It is our opinion that increasing this is unnecessary. The final data reduction is managed by a routine called PLMOD (for plate modeling).

As for SSC, communication is handled via a CRT display device and three buttons on the operator's console. Their functions are as before. Fig. 2 illustrates the dialogue. Final presentation and recording of the data is also similar. The novel feature is that hidden from both the operator and PLMOD is the fact that one of the five reference stars is used as a control on the entire observing process and computational procedure. Hence, PLC produces unbiased, absolute, external values for the total error in the object of interest's direction. To further minimize the effects of an unmodeled personal equation, the order of observation is random.

The final point on the mechanics of the process concerns the automatic, but iteratively self-correcting, gross movement of the telescope and a continuous refreshing of the finding chart. DISPLAY controls this by placing

```
GO OUT OF ZOOM.  SIZE OF DISPLAY FIELD IS 2.0 DEGS CAN YOU RECOGNIZE THE
FIELD?  TYPE y OR n:
y
SWITCH TO ZOOM AND BORESIGHT BLINKING STAR.
IF YOU CAN BORESIGHT PRESS DATA BUTTON
IF NOT PRESS NO DATA.
FIELD SIZE IS 1.5 DEGS.
YOU WILL BE BORESIGHTING 4 STARS
TRY TO BORESIGHT STAR #1
TRY TO BORESIGHT STAR #2
TRY TO BORESIGHT STAR #3
TRY TO BORESIGHT STAR #4
BORESIGHT LOOP COMPLETED,NO STARS LEFT.
UNKNOWN'S RIGHT ASCENSION =  3 46 37.9 DECLINATION =  30 8 32
ERRORS IN RA*COS(DEC) =   5.2 DEC =   6.2 POS =  8.1
```

(Message if unable to recognize field)

```
THIS PROGRAM WILL END.  TRY TO GET THE SATELLITE BACK OR USE SSC TO
CALIBRATE.
```

(Possible message following boresighting of center star)

```
THE FIELD IS TOO FAR OFF.
```

(Message if no data pressed too often)

```
CONFUSION ON TOO MANY STARS.
```

(Messages if unable to activate any of associated tasks)

```
ACTIVATION ERROR IN VGDISP 2
ACTIVATION ERROR IN FINCAL 1
ACTIVATION ERROR IN GETSTR 1
```

Fig. 2. Interactive dialogue for PLC. Operator responses are in lower case letters.

a blinker of the appropriate size and intensity directly under the next reference star to be observed. Sample displays are illustrated in Figs. 3-11. These cover a larger area than the real time display does only for illustrative purposes. We have adopted the following notation: (1) stars are represented as points or filled circles (to mimic the purely electronic blooming in the camera) of the appropriate intensity. This is governed by the star's apparent magnitude, (2) asteroids will be represented by letter A, (3) galactic clusters and globular dusters in the NGC are represented by the letter C, (4) galaxies in the NGC or IC are represented by the letter G, and (5) nebulosities in the NGC or IC are represented by the letter N. In each instance, the size and intensity of the symbol is governed by the apparent magnitude.

By construction PLC requires no external checks. Nonetheless, in the interests of completeness experimental verification of this fact will be obtained. Preliminary results, both theoretical and observational, suggest that PLC will invariably supply positional accuracy well in excess (at least a factor of 2) of that required. It is also our opinion that it exists, now, in its final state.

P41-1618

Fig. 3. The field (2°75 diameter) of the Andromedia Nebula (M31) showing also NGC205 and M32.

Fig. 4. The heart of the Orion association. The field is 5° in diameter and the large N represents M42 (the Orion Nebula).

P41-1617

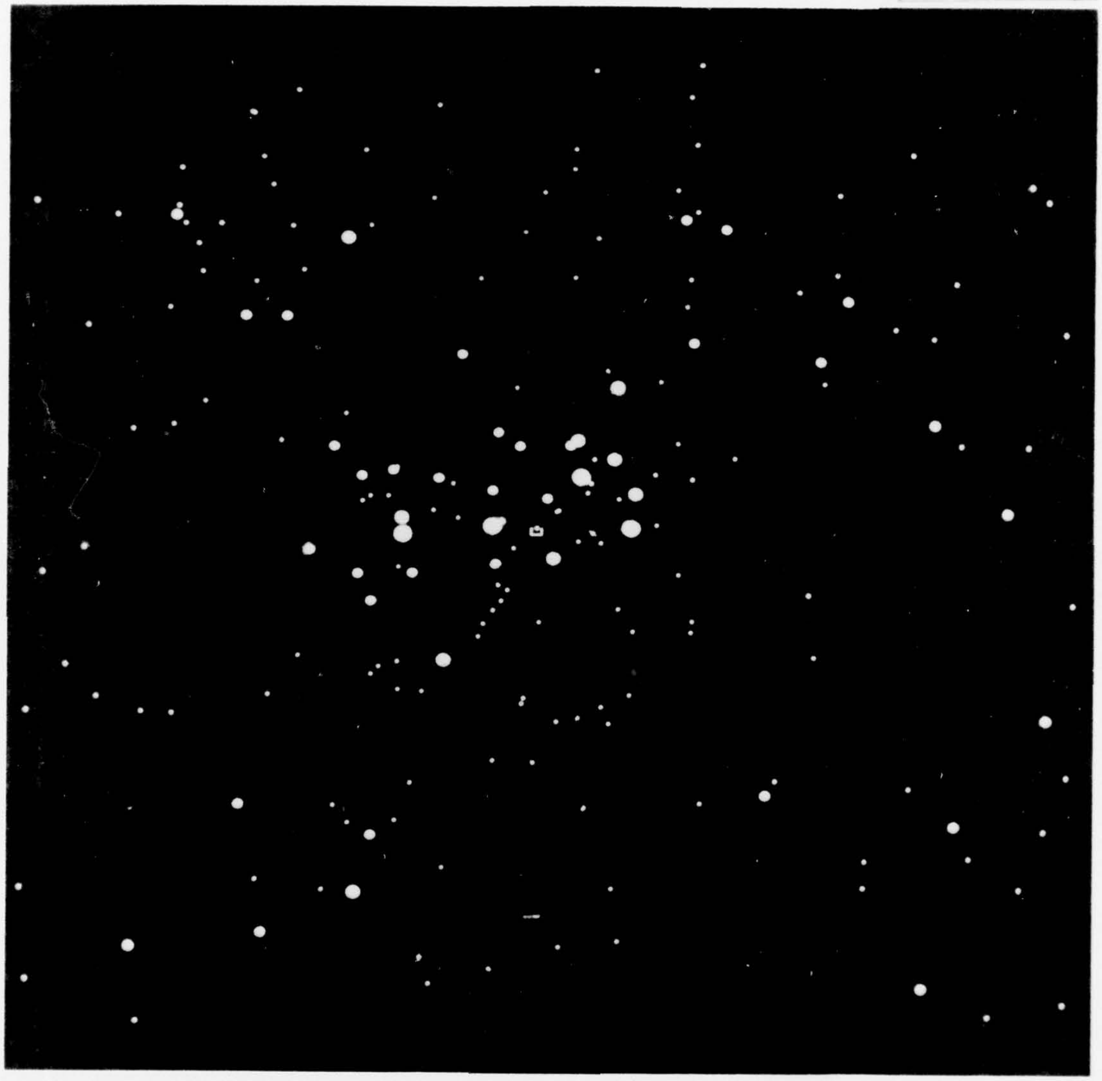

Fig. 5. The Pleiades (5° diameter field).

P41-1611

Fig. 6. The galactic cluster M6 (5° diameter field).

P41-1619

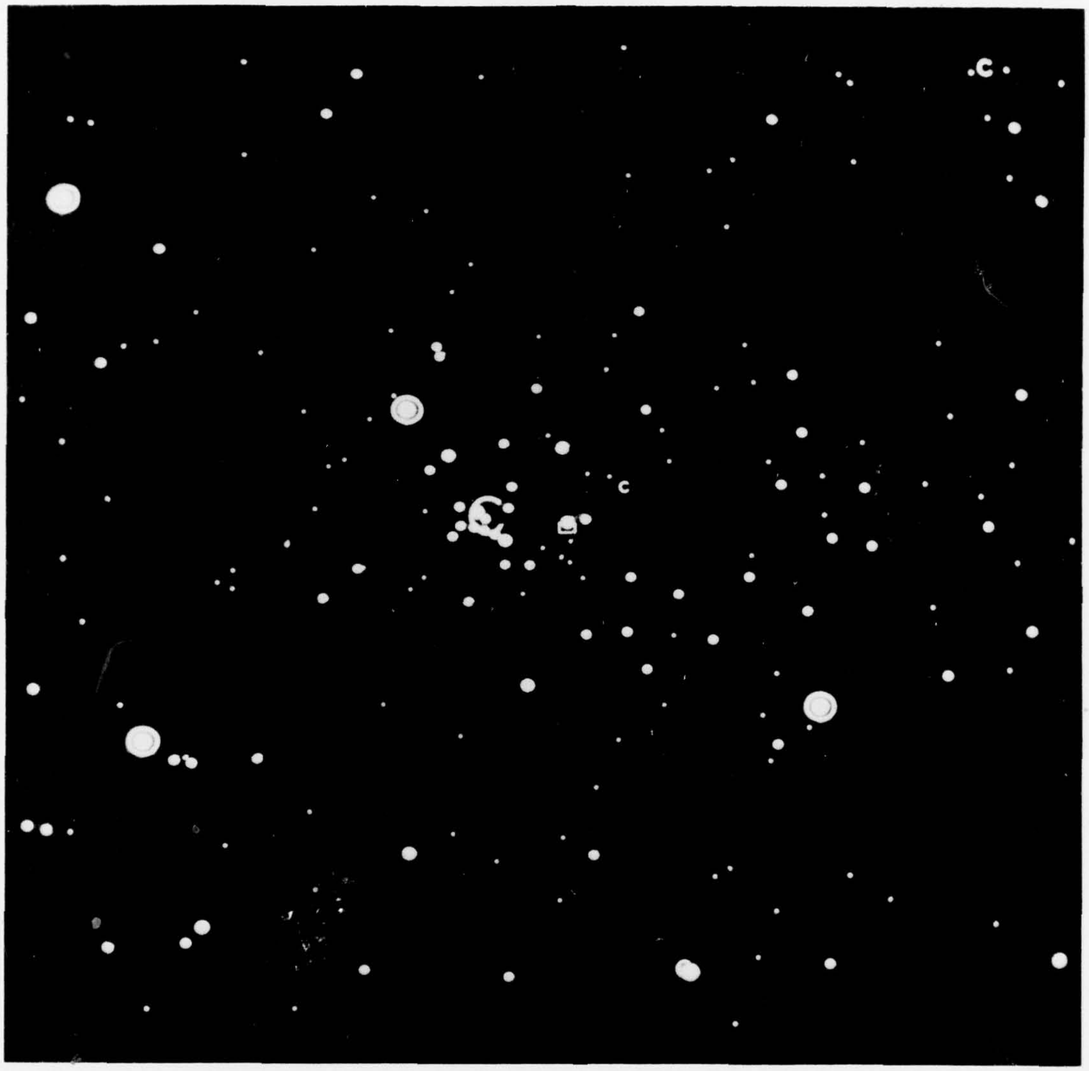

Fig. 7. The galactic cluster M7 (5° diameter field).

P41-1612

Fig. 8. The double cluster, h + χ Persei, (5° diameter field).

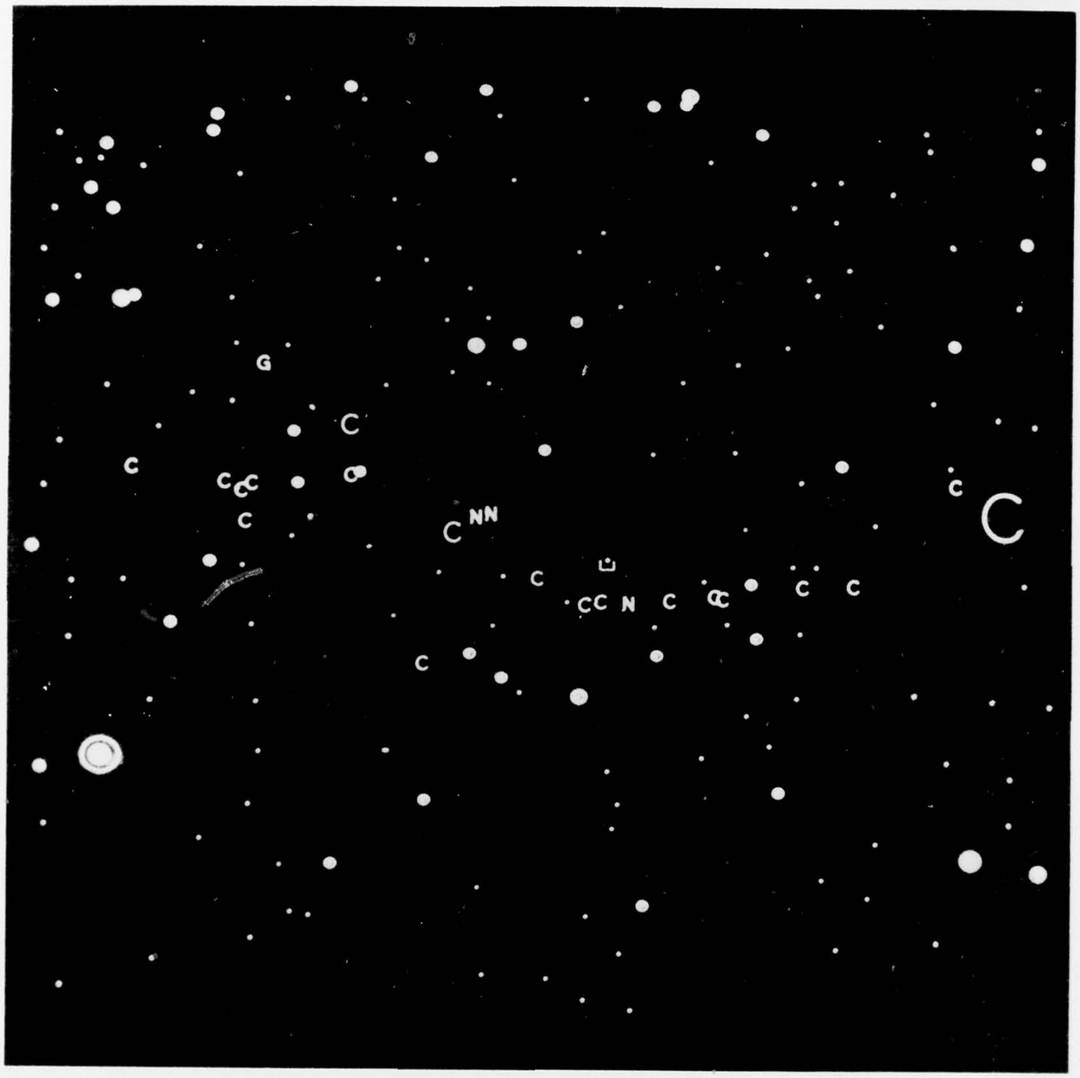

Fig. 9. The Small Magellanic Cloud (15° diameter field).

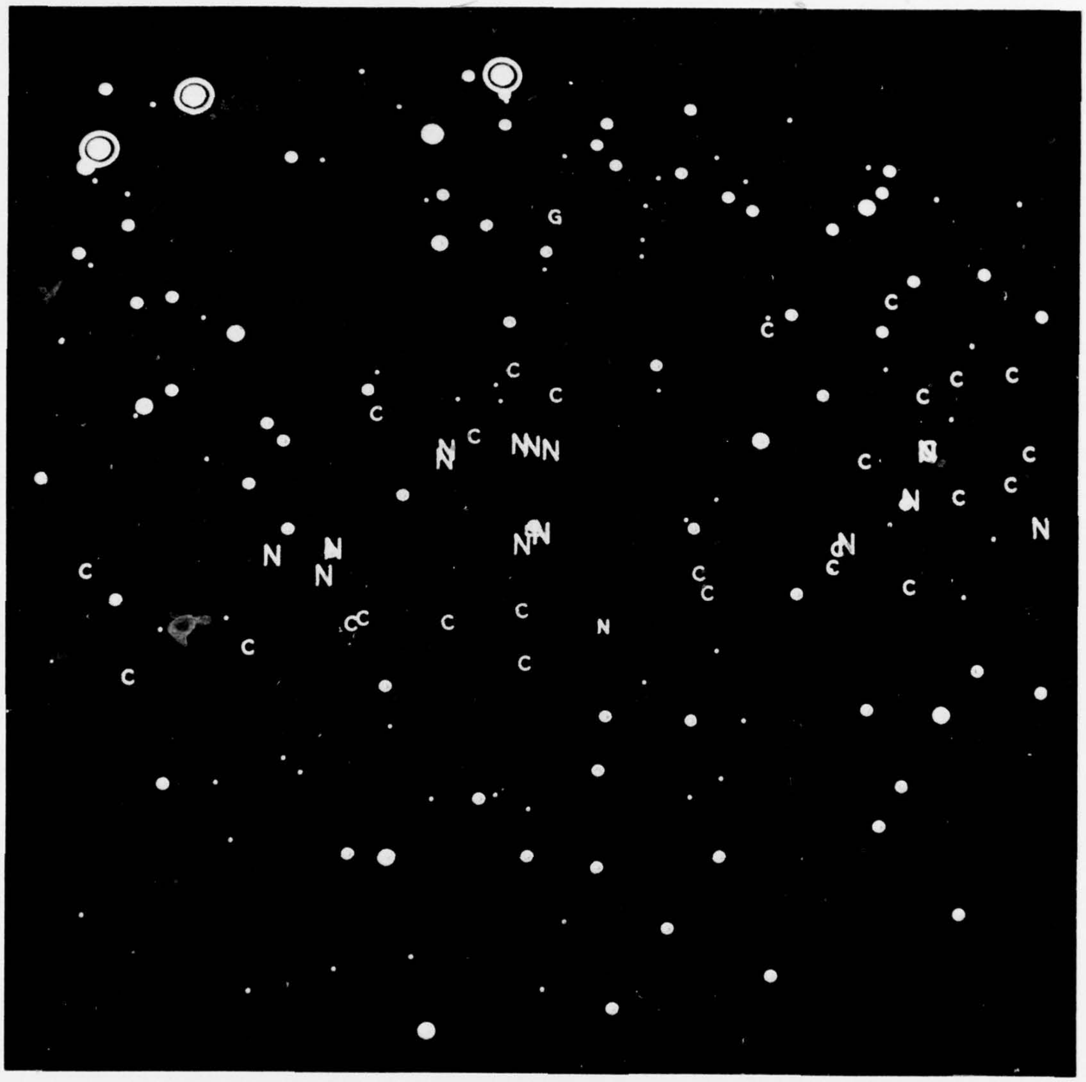

Fig. 10. The Large Magellanic Cloud (15° diameter field).

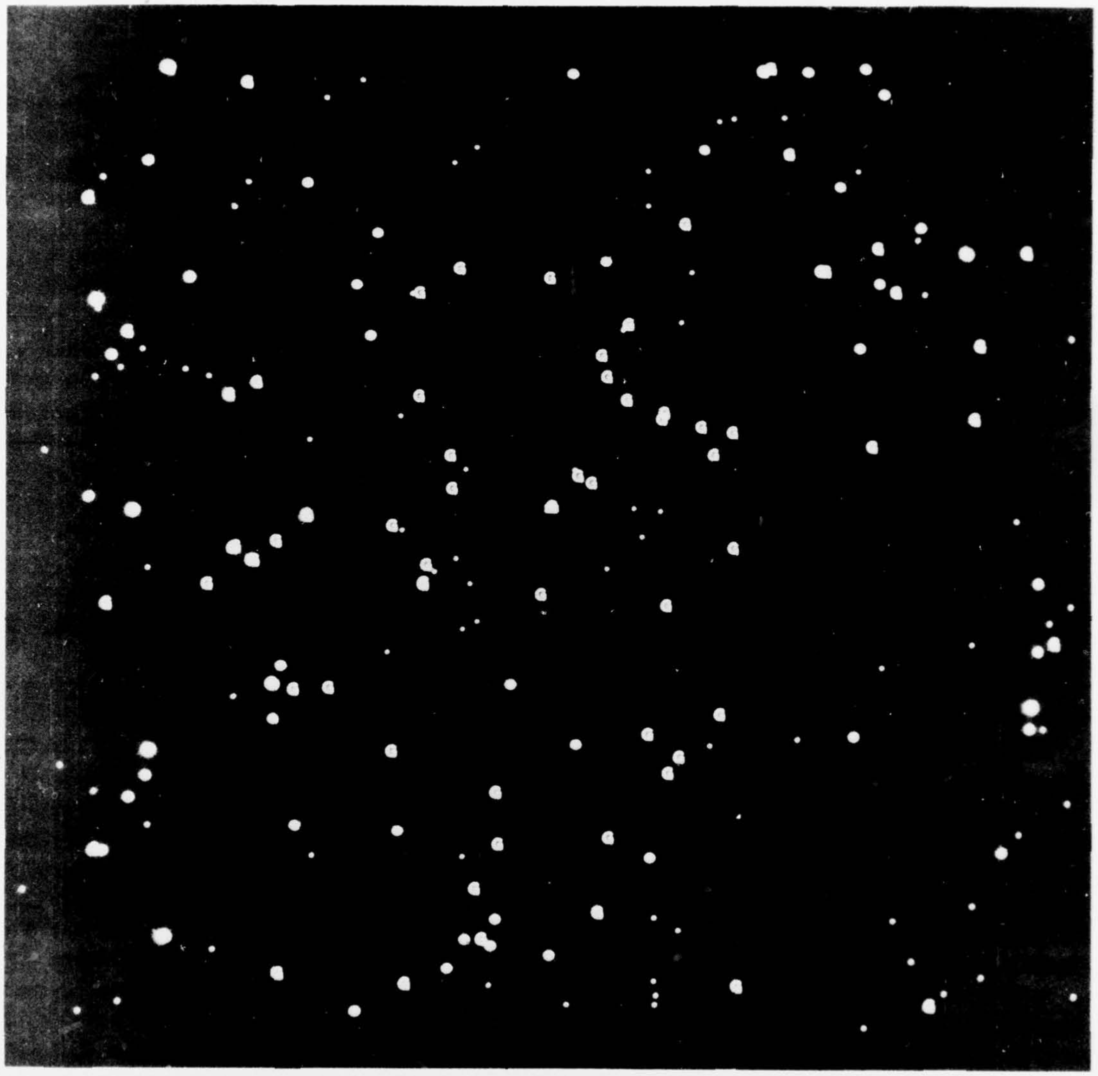

Fig. 11. A portion of the Virgo cluster of galaxies (10° diameter field).

VI. ULTIMATE ASTROMETRY

A last possibility, which represents the true amalgam of classical photographic astrometry and the solid state technology of the 1980's, is the real-time reduction of the camera target. That is, to read directly the coordinates and magnitudes of the images of the various celestial objects. This technique has been investigated (a brief outline is given below) but its implementation delayed until the practical advent of charge coupled devices.

The reasons for the delay are connected with some of the problems peculiar to externally intensified, electron bombarded, silicon-diode array, electron beam cameras. Those aspects of such devices that we expect to cause trouble are known as shading, lag, ionic scintillation, geometric distortion, image rotation, beam stealing, edge resolution, limited integration time, the occurrence of blemishes, and image blooming. Of course, the latter three are also imperfections of CCD cameras too.

If a charge coupled device camera can overcome a sufficient number of these problems* then we envision the following scenario: The right ascension and declination of the center of the field imaged on the focal plane is known. This is the tangential point on the celestial sphere. From the CCD target itself we obtain rectangular coordinates and brightnesses. From the star catalogue and the properties of a gnomonic projection we have (or can compute) magnitudes and standard coordinates. Then a combination of distance, position angle, and magnitude is used to perform a correlation

*One can, presumably, always model all of these aberrations away. A very complex model requires a large amount of input data, e.g., known and measured stars. This, of course, requires an extensive, new, star catalogue.

between the measured values and the theoretical values. This would allow for field rotation, scale changes, field translation, other geometrical aberrations, and incompleteness. Once a match is made the projection is inverted and the unknown's topocentric coordinates immediately obtained. A version of the matching program already exists at the SAO. The majority of the other necessary software has been developed for PLC.

VII. SUMMARY

Which procedure should you use? If Global Calibration can be successfully demonstrated (at the required level of precision) it is the clear-cut choice for routine operation. In this case, SSC should be reserved for emergency situations. In the absence of Global Calibration, SSC is the choice for routine operation. Independent of these two, PLC will always serve as the ultimate technique. It will always yield results of the consistently highest accuracy, invaluable error estimates, and require the most computer time, telescope time, and operator cooperation. Hence, it should probably be reserved for special cases.

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astrometric reduction	computer controlled	photometric calibration
GEODSS	electro-optical	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the present status of the implementation of real-time positional data reduction at the GEODSS Experimental Test Site. The report embraces definitions of the various procedures which have been explored, their respective futures, their accuracies and precisions, their source files, and how the operator interacts with these procedures in a computer controlled electro-optical artificial satellite observatory. The Introduction contains references to the documents that describe the underlying philosophy, theoretical and practical foundations, and computational details.

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